

Recent results of the STAR high-energy polarized proton-proton program at RHIC at BNL

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Abstract. The STAR experiment at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) is carrying out a spin physics program colliding transverse or longitudinal polarized proton beams at $\sqrt{s} = 200 - 500$ GeV to gain a deeper insight into the spin structure and dynamics of the proton. These studies provide fundamental tests of Quantum Chromodynamics (QCD).

One of the main objectives of the STAR spin physics program is the determination of the polarized gluon distribution function through a measurement of the longitudinal double-spin asymmetry, A_{LL} , for various processes. Recent results will be shown on the measurement of A_{LL} for inclusive jet production, neutral pion production and charged pion production at $\sqrt{s} = 200$ GeV. In addition to these measurements involving longitudinal polarized proton beams, the STAR collaboration has performed several important measurements employing transverse polarized proton beams. New results on the measurement of the transverse single-spin asymmetry, A_N , for forward neutral pion production and the first measurement of A_N for mid-rapidity di-jet production will be discussed.

Keywords: BNL, RHIC, STAR, pp collisions, QCD, proton spin, A_{LL} , A_N , gluon polarization, orbital angular momentum, Collins effect, Sivers effect

PACS: 12.38.-t, 13.85.Ni, 13.87.-a, 13.87.Fh, 13.88.+e, 14.70.Dj

INTRODUCTION

The core goal of the RHIC spin program is to obtain a deeper understanding of the spin structure and dynamics of the proton in polarized proton-proton collisions [1]. Shedding light on the proton spin puzzle by providing insight on how the intrinsic spin of the proton is distributed among its underlying constituents of quarks, anti-quarks and gluons is an important aspect of the program. Determination of the parton orbital angular momentum contributions and gluon helicity distribution are essential for a complete understanding of the proton spin.

The RHIC facility is the first polarized collider, providing collisions of transverse or longitudinal polarized proton beams at a center-of-mass energy of $\sqrt{s} = 200$ GeV and in the future of $\sqrt{s} = 500$ GeV. The STAR spin physics program has profited enormously from the steady improvement and development of the RHIC polarized proton-proton collider facility in terms of polarization and luminosity. The performance of the most recent run in 2006 (Run 6) is very encouraging with an average polarization of 60% and a delivered luminosity per day of approximately 1 pb^{-1} at $\sqrt{s} = 200$ GeV. This is to be compared with the design performance of 70% in beam polarization and a daily delivered luminosity of approximately 3 pb^{-1} at $\sqrt{s} = 200$ GeV. Several anticipated improvements along with the required subsequent development of the RHIC facility are expected to yield the design performance at $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV [2]. An

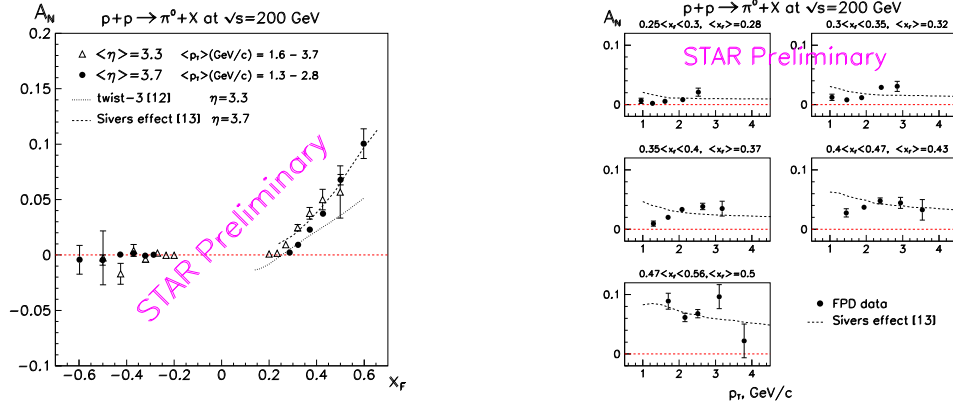


FIGURE 1. (left) A_N as a function of x_F for $p + p \rightarrow \pi^0 + X$ from Run 6. The error bars represent statistical errors only. Systematic uncertainties are smaller than statistical uncertainties. The dotted line represents the result of a twist-3 calculation [19], whereas the dashed line is the result of a calculation based on the Sivers effect [20]. (right) A_N as a function of p_T for $p + p \rightarrow \pi^0 + X$ from Run 6 in bins of x_F in comparison to a calculation based on the Sivers effect [20].

important step for the STAR spin physics program was the first transverse single-spin asymmetry measurement in forward neutral pion production from the first polarized proton-proton run in 2002 (Run 2) [3] and the first longitudinal double-spin asymmetry measurement sensitive to the gluon polarization in mid-rapidity inclusive jet production from Run 3 / 4 [4].

The following two sections will highlight recent results [5, 6, 7, 8, 9, 10, 11] of the STAR transverse and longitudinal spin physics program.

STAR TRANSVERSE SPIN PROGRAM - RECENT RESULTS

The study of transverse spin effects, both theoretically and experimentally, has received a lot of attention in recent years. The ultimate goal of this effort is to extract transversity distribution functions and determine possible orbital angular momentum contributions of quarks, anti-quarks and gluons to the proton spin [12].

The first measurement of a transverse single-spin asymmetry, A_N , at $\sqrt{s} = 200$ GeV for forward neutral pion production at $3.3 < \eta < 4.1$ by the STAR collaboration [3] was found to increase with x_F similar in magnitude to the measurement of A_N performed by the E704 experiment at $\sqrt{s} = 20$ GeV [13]. The STAR collaboration has performed cross-section measurements for forward neutral pion production at $\langle \eta \rangle = 3.3, 3.8$ and 4.0 , which are found to be in good agreement with next-to-leading order (NLO) perturbative QCD calculations [14]. This provides an important basis for the interpretation of the sizable measured asymmetries at forward rapidity. Several models beyond a conventional collinear perturbative QCD approach are able to account for the measured asymmetries. These models are based on three main correlation concepts: A correlation of the parton intrinsic transverse momentum k_T and the proton spin in the initial state (Sivers effect) [15], a correlation between the quark spin and the hadron k_T in

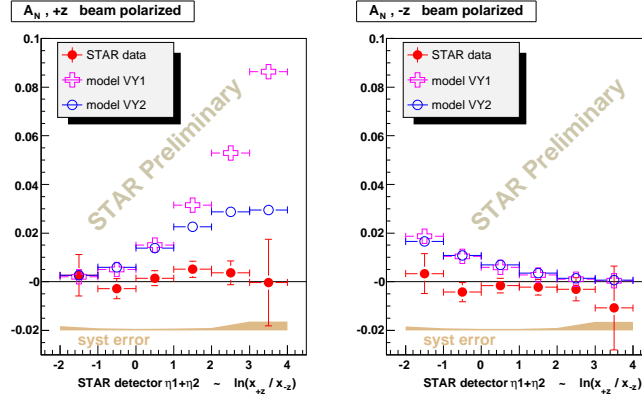


FIGURE 2. Transverse single-spin asymmetries for A_N^{+z} (left) and A_N^{-z} (right) as a function of $\eta_1 + \eta_2$ for di-jet production at $\sqrt{s} = 200 \text{ GeV}$ from Run 6 in comparison to theoretical calculations [23, 24].

the final state (Collins effect) [16] and a higher twist correlation in the initial and final state [17, 18]. The STAR collaboration has performed an upgrade of their Forward Pion Detector (FPD) for Run 6 as a prototype for the Forward Meson Spectrometer (FMS). The main goal is to disentangle different mechanisms responsible for the observed large transverse single-spin asymmetries in the forward direction. New results of forward neutral pion production at higher precision are shown in Figure 1 [7]. These results are in good agreement with previous results. The measured asymmetry A_N is found to be consistent with zero at negative x_F and grows from 0 at $x_F \simeq 0.2 - 0.3$ up to 0.1 at $x_F \simeq 0.6$. Figure 1 shows also the result of two calculations at different $\langle \eta \rangle$ values [19, 20]. The measured asymmetries are precise enough to allow for a quantitative comparison with theory predictions. The extended kinematic region in x_F and p_T and the increase in the available data sample from Run 6 allowed for the first time for a mapping of A_N in x_F and p_T . Figure 1 shows A_N as a function of p_T in fine bins of x_F . The current measured result of A_N do not support a decreasing behavior of A_N in p_T in all x_F bins as expected by various theoretical models.

A possible manifestation of orbital angular momentum effects could be realized through a non-zero Sivers type correlation of the parton intrinsic transverse momentum k_T and the proton spin in the initial state. The HERMES collaboration has recently reported a non-zero Sivers function in semi-inclusive DIS for π^+ production [21]. The Sivers function for π^- production has been found to be consistent with zero. This led to the interpretation that the Sivers functions are opposite in sign and different in magnitude for u compared to d quarks. The study of Sivers type correlations in polarized proton-proton collisions has been considered in [22]. The theoretical expectation is that the Sivers effect would be reflected in a spin-dependent side-ways boost to the di-jet opening angle. A measurement of the correlation between the spin direction and di-jet bi-sector direction would be needed. A dedicated Level 2 di-jet trigger, utilizing the STAR Barrel and Endcap Electromagnetic Calorimeters (BEMC and EEMC), was implemented during Run 6.

Figure 2 shows the measured transverse single-spin asymmetry, A_N , for di-jet production as function of $\eta_1 + \eta_2$ for both polarized beams in the $\pm z$ direction [5]. The region

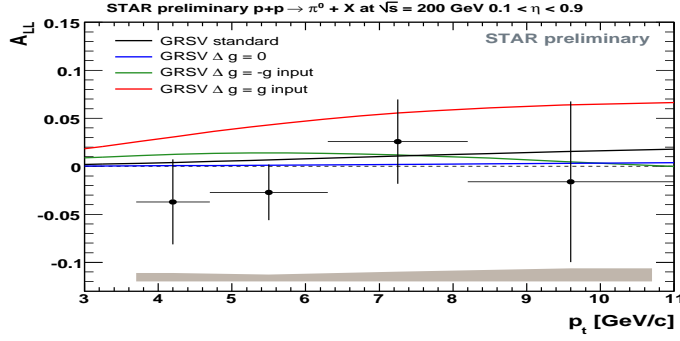


FIGURE 3. Longitudinal double-spin asymmetry A_{LL} for neutral pion production at $\sqrt{s} = 200 \text{ GeV}$ as a function of p_T ($0.1 < \eta < 0.9$) for Run 5 in comparison to several gluon polarization scenarios.

of large $\eta_1 + \eta_2$ values emphasizes quark (gluon) Sivers effects for $+z$ ($-z$). In both cases, the measured transverse single-spin asymmetries are found to be consistent with zero. The measured results are compared to predictions based on u and d quark Sivers functions extracted from measured HERMES semi-inclusive DIS data, which assume a zero gluon-type Sivers function [23, 24]. The calculations were carried out using only gauge-link factors for initial-state interactions, as expected for Drell-Yan production. Further modifications are required for di-jet production taking into account final-state effects. Theoretical work on the proper treatment of these final-state effects is ongoing.

Further theoretical work is needed to account for both the large transverse single-spin asymmetries for forward neutral pion production and the recent di-jet result from STAR in polarized proton-proton collisions, as well as the results obtained in semi-inclusive DIS. The STAR Forward Meson Spectrometer, which is expected to be operational in the 2007 RHIC run, will provide a full azimuthal coverage at $2.5 < \eta < 4.0$. This detector system will allow STAR to isolate Sivers from Collins effects. It will extend the jet, photon and neutral pion acceptance of the STAR experiment, which will be also of considerable interest for the longitudinal spin program.

STAR LONGITUDINAL SPIN PROGRAM - RECENT RESULTS

The longitudinal STAR spin physics program profits enormously from the unique capabilities of the STAR experiment for large acceptance jet production, identified hadron production and photon production [25]. The measurement of the gluon polarization through inclusive measurements such as jet production and π^0 production has been so far the prime focus of the physics analysis program of the Run 3/4 and Run 5 data samples. The sensitivity of these inclusive measurements to the underlying gluon polarization in high-energy polarized proton-proton collisions has been discussed in detail in [26]. Inclusive hadron production and jet production are strongly affected by the relative contributions from quark-quark, quark-gluon and gluon-gluon subprocesses. The low p_T region is dominated by gluon-gluon scattering, while at high p_T the quark-gluon contribution starts to become important. As a result, the sign of A_{LL} in this high p_T region indicates the sign of the gluon polarization. The fact that the inclusive photon channel

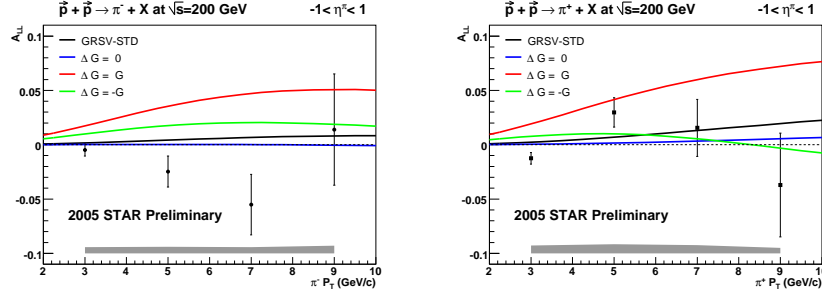


FIGURE 4. Longitudinal double-spin asymmetry A_{LL} for charged pion production at $\sqrt{s} = 200$ GeV as a function of p_T ($-1 < \eta < 1$) for Run 5 in comparison to several gluon polarization scenarios.

is dominated by quark-gluon scattering results in a strong sensitivity to the underlying gluon polarization, despite the small production cross-section. Throughout the following discussion, four gluon polarization scenarios have been used as input to NLO perturbative QCD calculations of A_{LL} . The GRSV standard case refers to the best global analysis fit to polarized DIS data [27]. The case for a vanishing gluon polarization (GRSV-ZERO) and the case of a maximally positive (GRSV-MAX) or negative (GRSV-MIN) gluon polarization have been also considered.

The first longitudinal double-spin asymmetry measurement for inclusive jet production and the associated inclusive jet cross-section measurement at mid-rapidity has recently been published [4]. The measured asymmetries are consistent with NLO perturbative QCD calculations based on DIS polarized lepton-nucleon data, and disfavor a large positive value of the gluon polarization in the proton. In addition, the STAR collaboration has recently released a preliminary result on the inclusive neutral pion production cross-section at mid-rapidity [28]. The (unpolarized) cross-section measurements of inclusive jet and neutral pion production support the asymmetry measurements at RHIC by validating the applicability of perturbative QCD.

The following measurements of A_{LL} from Run 5 at $\sqrt{s} = 200$ GeV [6, 8, 9, 10] for identified hadron production and inclusive jet production are based on an average beam polarization of approximately 50% and a data sample of approximately 3 pb^{-1} . The overall normalization uncertainty due to conservative error estimates on the preliminary polarization values amounts to $\sim 40\%$. All A_{LL} analyses presented below make use of the STAR BEMC and EEMC system at the trigger and reconstruction level. A high-tower (HT1 / HT2) trigger is based on an energy threshold above 2.6 (3.5) GeV for a single tower ($\Delta\eta \times \Delta\phi = 0.05 \times 0.05$) whereas a jet-patch (JP1 / JP2) trigger is based on an energy threshold above 4.5 (6.5) GeV for a group of towers over a region in η and ϕ of $\Delta\eta \times \Delta\phi = 1.0 \times 1.0$. Both triggers are taken in coincidence with a minimum-bias condition using the STAR Beam-Beam Counter.

Figure 5 shows the measured longitudinal double-spin asymmetry A_{LL} for neutral pion production as a function of p_T together with different gluon polarization scenarios as described above. The error bars include statistical uncertainties only. The systematic error band includes contributions from the neutral pion yield extraction and background subtraction, remaining background, possible non-longitudinal spin contributions and the relative luminosity uncertainty. This analysis is based on a fraction of the Run 5

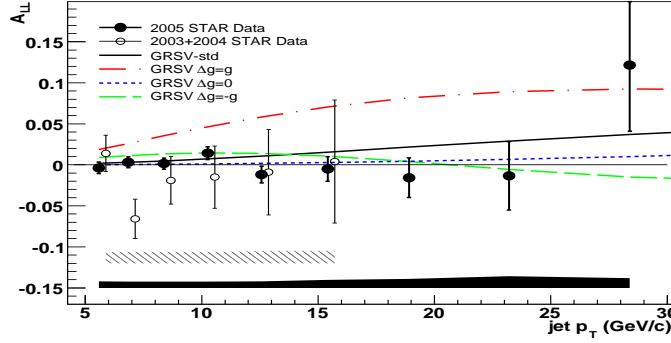


FIGURE 5. Longitudinal double-spin asymmetry A_{LL} for inclusive jet production at $\sqrt{s} = 200 \text{ GeV}$ as a function of p_T ($0.2 < \eta < 0.8$) for Run 5 in comparison to several gluon polarization scenarios.

data sample for a restricted pseudo-rapidity region. Data from Run 6 will include the full acceptance of the STAR BEMC. The data tends to disfavor a large positive gluon polarization scenario.

In addition to the first neutral pion analysis of A_{LL} at mid-rapidity, the STAR collaboration has recently presented the first preliminary result of neutral pion production using the STAR EEMC in the pseudo-rapidity acceptance region of $1.086 < \eta < 2.0$ from Run 5 [10]. The data are consistent with zero over the p_T range of $3 < p_T < 7 \text{ GeV/c}$, albeit with large statistical uncertainties. The systematic uncertainties are comparable to the statistical uncertainties and dominated by beam induced background. These background contributions were observed to be suppressed by a factor 20 during Run 6 relative to those in Run 5 profiting from the installation of shielding to reduce beam induced background prior to Run 6. This EEMC based analysis provides an important baseline measurement for future prompt photon measurements in the STAR EEMC acceptance region.

The STAR collaboration has presented the first measurement of the longitudinal double-spin asymmetry A_{LL} for inclusive charged pion production during Run 5. The asymmetries are calculated over the transverse momentum region $2 < p_T < 10 \text{ GeV/c}$ and compared to several gluon polarization scenarios as described earlier. This analysis is unique in that the difference $A_{LL}(\pi^+) - A_{LL}(\pi^-)$ tracks the sign of the gluon polarization, due to the opposite signs of the polarized distribution functions for up and down quarks. The STAR TPC offers robust reconstruction and identification of charged pions over the transverse momentum range $2 < p_T < 10 \text{ GeV/c}$. Particle identification in the TPC is accomplished using measurements of ionization energy loss of TPC hits. Figure 4 shows preliminary results during Run 5 for charged pion production. The measured asymmetries are compared to theoretical predictions for A_{LL} based on different gluon polarization scenarios. The fragmentation functions for π^+ and π^- are based on the KKP fragmentation functions [29]. This first measurement of A_{LL} for charged pion production disfavors as well a large gluon polarization scenario. Several systematic checks have been performed. The leading systematic uncertainty accounts for the bias introduced by the trigger used for this analysis. This trigger is based on a jet patch trigger,

which introduces a bias towards jets with a large fraction of neutral energy. The impact of this trigger on the charge pion asymmetry analysis has been estimated using a MC sample and amounts to approximately $5 \cdot 10^{-3}$, which is comparable to the statistical uncertainty of the first p_T bin. In addition, asymmetries were calculated for trigger-jets in comparison to away-side jets. Both asymmetries have been found to be consistent within statistical uncertainties.

The STAR collaboration has recently released preliminary results of the measurement of the longitudinal double-spin asymmetry A_{LL} for inclusive jet production, which is shown in Figure 5 as a function of p_T for $5 < p_T < 30 \text{ GeV}/c$ in comparison to several gluon polarization scenarios as described earlier [8]. Jets are reconstructed using a midpoint cone clustering algorithm using a cone radius of 0.4. This algorithm is fed in the case of STAR by reconstructed electromagnetic clusters in the STAR BEMC and tracks from the STAR TPC. The uncertainties show statistical uncertainties only. Various systematic effects have been studied. The dominant contribution to the systematic uncertainties are due to false asymmetries, trigger bias and jet reconstruction bias. The 2005 A_{LL} inclusive jet measurement is found to be in good agreement with the previous 2003/2004 measurement. The current measurement extends the p_T region to larger values, where the quark-gluon contribution starts to become important. This analysis rules out a large gluon polarization scenario. It provides the most precise A_{LL} measurement to constrain the gluon polarization of the proton to date at RHIC.

Taking all current PHENIX [30, 31] and STAR A_{LL} measurements together in comparison to different NLO perturbative QCD predictions for A_{LL} yields a consistent picture which rules out a large gluon polarization scenario. The STAR inclusive measurements will benefit enormously from the increased data sample in Run 6, the larger beam polarization and the wider detector acceptance at central rapidity with the completion of the STAR BEMC. A critical aspect to extract the gluon polarization of the proton is to perform a global analysis of several A_{LL} measurements obtained from the PHENIX [30, 31] and STAR collaborations taking into account a constraint of polarized parton distribution functions at high Bjorken- x values by several polarized fixed-target DIS experiments. All the required full NLO calculations exist and have been incorporated into a full NLO global analysis framework [32, 33, 34].

STAR will extend its existing inclusive jet measurements to di-jet measurements. This will allow a better constrain of the underlying event kinematics to extract the shape of the gluon polarization in a global analysis [34]. Photon-jet coincidence measurements are expected to provide a theoretically clean way to extract the polarized gluon distribution. Measurements at both $\sqrt{s} = 200 \text{ GeV}$ and $\sqrt{s} = 500 \text{ GeV}$ are preferred to maximize the kinematic region in x as well as to provide a means to measure the effect of scaling violations at fixed Bjorken- x , but different p_T values.

The STAR collaboration has presented a proof-of-principle measurement of the longitudinal spin transfer D_{LL} in inclusive Λ ($\Lambda \rightarrow p\pi^-$) and $\bar{\Lambda}$ ($\bar{\Lambda} \rightarrow \bar{p}\pi^+$) production in polarized proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 200 \text{ GeV}$ at a mean transverse momentum p_T of about $1.3 \text{ GeV}/c$ and a longitudinal momentum fraction of $x_F = 7.5 \times 10^{-3}$. The measurement of D_{LL} for inclusive Λ and $\bar{\Lambda}$ production may provide constraints on strange (anti) quark polarization [35] and can yield new insight into polarized fragmentation functions [36]. The extension of the p_T region to large values is essential.

The production of $W^{-(+)}$ bosons provides an ideal tool to study the spin-flavor structure of the proton. $W^{-(+)}$ bosons are produced in $\bar{u} + d(u + \bar{d})$ collisions and can be detected through their leptonic decay [37, 38]. An upgrade of the STAR forward tracking system is currently in preparation to provide the required tracking precision for $W^{-(+)}$ charge sign discrimination in the acceptance region of the STAR EEMC in the electron (positron) decay mode [39]. The W physics program requires RHIC running of longitudinal polarized proton beams at a center-of-mass energy of $\sqrt{s} = 500 \text{ GeV}$ at high luminosity and polarization.

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